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Concentric spectrographs

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A novel class of geometric optical configurations for diffraction grating spectrographs is introduced. Th concentric configurations offer appreciable advantages over traditional arrangements. Excellent imag quality at high numerical aperture is demonstrated experimentally.

Almost two decades ago, Dyson[1] described an elegant concentric unit-magnification optical system which aroused a speculation[2] that the system may be converted to a spectrograph by introducing diffraction grating grooves on the concave reflecting surface to give the configuration shown in Fig. 1. Because the grating surface is so deeply concave, verification really awaited the advent of holographic diffraction gratings. A rudimentary prototype version of the spectrograph (200 Å/mm, $f/1$, with 7.6-cm grating diameter and using a grating furnished courtesy of the Jobin-Yvon Optical Company) has since confirmed the image quality. The advantageous features of this particular concentric configuration are

(1) sharp imagery due to the inherent absence of Seidel aberrations;

(2) high numerical aperture; N.A. > 0.6 is practicable;

(3) stigmatic;

(4) flat field;

(5) wide unvignetted field having linear dispersion as a function of wavelength, covering the complete photographic spectral range and permitting long slits;

(6) readily accessible field located on the exterior of the spectrograph;

(7) nonanamorphic field; equal magnification along and across the dispersion is important for convolution applications;

(8) telecentric with the pupil situated at infinity, focusing errors introduce neither dispersion change nor asymmetric instrument profiles;

(9) no central obscuration of the pupil;

(10) no aspherical optical surfaces are required.

The restrictions of the configuration are (a) that the spectrograph is limited to low dispersion, (b) transmitting material is required, (c) its focal ratio does not directly match that of telescopes, and (d) its diffraction grating must be holographically formed.

It is the symmetry given to each ray by the concentricity of the optics that is responsible for the clean imagery. There can be no skew rays, the sagittal focus is rigorously a plane through the center. When the configuration is retroreflective, the ingoing and outgoing ray intercepts of that plane are equidistant on opposite sides of the center for any ray. That in conjunction with the concentricity establishes that the tangential focus is also sharp and coincident with the sagittal focus. If the hemisphere should not be complete, but simply a thick condensing lens for reasons of convenience, the only aberration introduced is the spherical aberration of the plane-parallel glass that is absent.

The configuration served as the basis for a project to construct two larger and more consonant spectrographs than the prototype. Their characteristics were planned to be 100 Å/mm, $f/0.9$, with 15-cm grating diameter. Fortuitously the cost of commercially available gratings proved far higher than anticipated and too expensive for the budget. That circumstance dictated in-house fabrication of the gratings, thereby not only bringing the benefits of a useful facility but also a preferable manufacturing technique could be employed.

The usual technique is to form holographic fringes, which delineate the grooves of the diffraction grating, by intersecting two large, coherent, and collimated beams of green laser light. The necessary collimators are large and cumbersome, and the whole setup is extremely susceptible to vibration.

Instead, two coherent point sources may be formed with a miniature interferometer employing two microscope objectives as shown in Fig. 2 and used in conjunction with the optical and mechanical parts of the spectrograph itself. Although this interferometer may seem asymmetric it has an equal number (2) of reflections in each arm and approximately equal pathlengths in each arm. The actual components are not adjustable,

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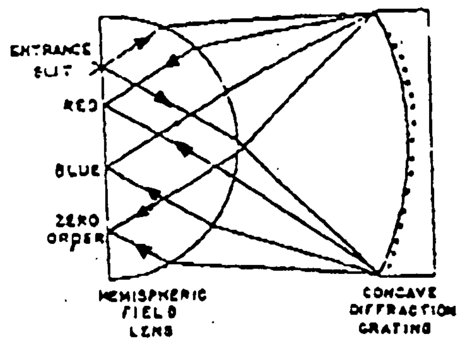

Fig. 1. Concentric spectrograph configuration.

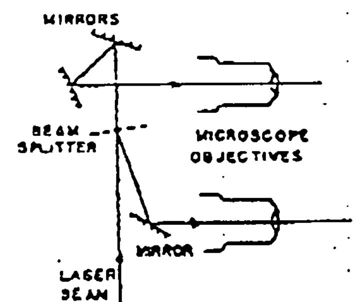

Fig. 2. Interferometer to form two coherent point sources for making the holographic diffraction grating.

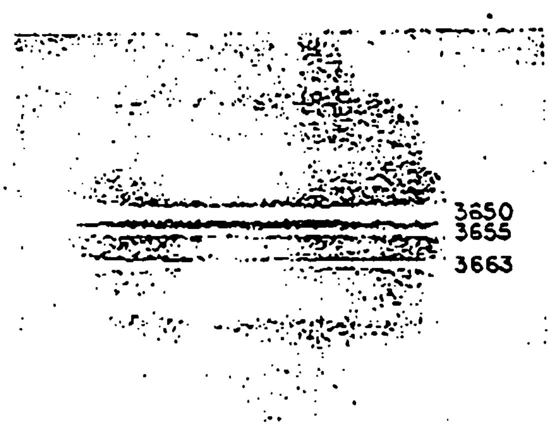

Fig. 3. Highly magnified print of small portion of mercury spectrum. Original emulsion 127-04, original dispersion ≈0.86 (~f/0.7).

good machining tolerances are sufficient to define their positions and tilts. Basically the placement of the point sources in the image plane of the spectrograph, at the zero and first order locations corresponding to the laser wavelength, provides Young's fringes at precisely the locations where the diffraction grating grooves should lie. Not only that, but the format of the grooves compensates any possible aberrations of the system at the laser wavelength.

A 10-mW cadmium laser served to expose photoresist coated surfaces following the recipes given by Labeyrie and Flamand[3] and Bartolini.[4] Compact solidity freed the setup from stability problems even with no antivibration structural supports.

The first resulting spectrograph had atrocious image quality with severe astigmatism, far worse than that of the prototype. Fortunately, the error was immediately evident. The paraxial curvature relations given by Dyson,[1] rather than retroreflectivity, had mistakenly been assumed to be vital. The device must be a good retroreflector only at the zone of the entrance slit to assure high image quality. The grating surface should lie at the principal focus of the hemispheric field lens, and the spherical aberration of that lens is so strong that for the zone of the specified slit location the grating surface radius reduced to 16 cm, as opposed to 20 cm for paraxial circumstances. Furthermore, the two point sources used for fabricating the grating should both be placed in that same zone, i.e., disposed on a chord rather than a diameter in the focal plane. The shorter radius grating has augmented the numerical aperture of the system to N.A. ≈ 0.86 (~f/0.7), which is perhaps a record for spectrographs. The actual elements are a 69-mm radius hemisphere of UBK-7 glass and a 135-mm concave grating with a 150-mm radius spherical surface, and the slit is 37 mm away from the center. The dispersion is approximately 100 Å/mm, and Fig. 3 illustrates the image quality attained.

During the course of the project Jean Flamand informed me that an all reflecting version of the configuration has been conceived by A. Thevenon. His design, shown in Fig. 4, is admirable, being a Schmidt

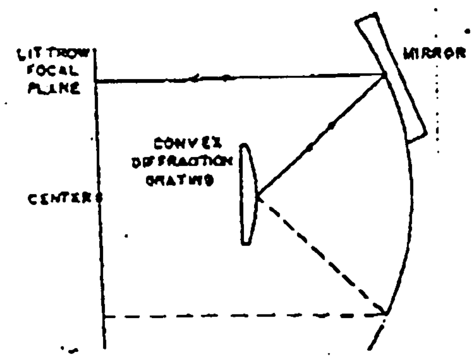

Fig. 4. Thevenon's all reflecting version. The lower portion is included only to show the family resemblance to a Schmidt telescope.

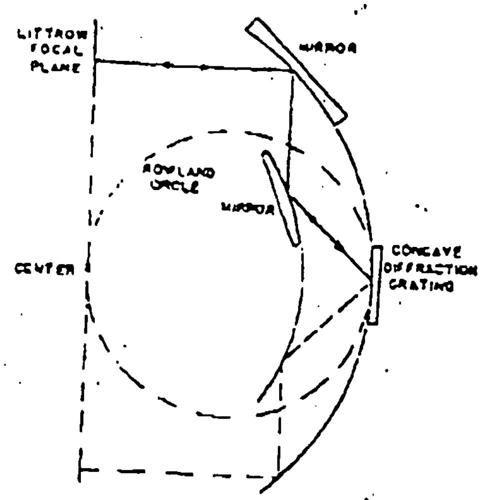

Fig. 5. Another all reflecting version suitable for ordinary concave gratings. The lower portion is included only to show the family resemblance to a Cassegrain-Schmidt telescope, and the Rowland circle is shown only for reference.

telescope with pupil and image locations interchanged. The image plane is now situated at the usual location of the corrector plate and the convex diffraction grating at the usual location of the telescope focus. Concentricity and the retroreflective property are sufficient conditions for ideal imagery.

Figure 5 illustrates a slightly more applicable scheme. This is just a Cassegrain-Schmidt telescope configuration and may be used with an ordinary ruled concave diffraction grating. With the relatively steep incidence angle on the grating it might have some merit over the simple Schmidt, since steep incidence leads to relatively high dispersion. The conventional Rowland circle for the grating is shown only for reference. Two reflections are seen to correct the customary astigmatism and give Littrow configurations with a concave diffraction grating.

The virtues of these concentric configurations open several paths. The combination of high numerical aperture with a long slit gives a high throughput that is cleanly matched to fiber optic image slicers. The ordinary difficulty with fiber optic slicers[4,6] is that even for collimated input beams, the light tends to spew out. If the spectrograph is not endowed with sufficient numerical aperture to accept that divergent output, much of the light can be lost. Inasmuch as the high numerical aperture of some of these concentric configurations readily exceeds that of fiber transmission, no such loss need occur. However we must be careful to appreciate that high speed, in the efficiency sense, does not necessarily follow from high numerical aperture in itself.[7]

The ultimate merit of these configurations lies mor the large number of independent pixels made av able.

If even more throughput than that available wit slit is required, the concentric spectrographs are ide suited as convolution spectrographs[9-11] because of th flat field, stigmatism, and nonanamorphism. Here noise characteristics of the detector must be such as partake a multiplex advantage if the convoluti techniques are to be beneficial. Experimental indic tions suggest that photographic detection can enjoy t multiplex advantage.[12]

Last, those same image properties that suit the co centric configurations to convolution techniques al open the path of mock interferometry.[9] The all r flecting versions thus extend the possibilities of Fouri transform spectrometry to the deep uv. Even thou the multiplex advantage is not available for uv dete tors, the augmented throughput may be beneficial employed for spectra of diffuse sources.

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